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Our long-term goal is to contribute to the understanding of the dynamics and stratification of exchange flows such as in the Bab al Mandab and to understand the consequences for the circulation in the neighboring basins and/or marginal seas.
One of the original objectives of the proposed work is to understand the effect of critical level mixing on the dynamics and stratification of sill flows. In particular, what happens when the mixing is limited to only the middle part of the water column, as appears to be the case in Bab al Mandab? When are such flows hydraulically controlled and to what extent are layer models with interfacial entrainment able to describe the hydraulic behavior. We also sought to formulate a model that captures the communication between the strait/sill system and the circulation and stratification in a connected basin.
A separate objective was to convene a meeting of the world's leading investigators of the physics of flow in sea straits in order to review the current state of knowledge and identify important topics of future research.

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Determining the Stratification of Exchange Flows in Sea Straits

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LONG-TERM GOALS

Our long-term goal is to contribute to the understanding of the dynamics and stratification of exchange flows such as in the Bab al Mandab and to understand the consequences for the circulation in the neighboring basins and/or marginal seas.

OBJECTIVES

One of the original objectives of the proposed work is to understand the effect of critical level mixing on the dynamics and stratification of sill flows. In particular, what happens when the mixing is limited to only the middle part of the water column, as appears to be the case in Bab al Mandab? When are such flows hydraulically controlled and to what extent are layer models with interfacial entrainment able to describe the hydraulic behavior. We also sought to formulate a model that captures the communication between the strait/sill system and the circulation and stratification in a connected basin.

A separate objective was to convene a meeting of the world's leading investigators of the physics of flow in sea straits in order to review the current state of knowledge and identify important topics of future research.

APPROACH

The conditions for hydraulic control in a continuously stratified flow were investigated through an analytical formulation of normal modes in flows with continuously varying stratification and shear, in channels of arbitrary cross sections. Investigations of critical level mixing and entrainment made use of a two-dimensional, non-hydrostatic model with continuous stratification. Initial-value experiments were performed in order to establish exchange flows having an interfacial region of finite thickness due to mixing (Figure 1). A previous theory based on a homogeneous shallow water formulation with cross-interface entrainment (Gerdes, et al. 2002) was tested. Effects on neighboring basins have been investigated using a numerical model of a basin flow drained by a single strait. The model has recently been extended to two layers.

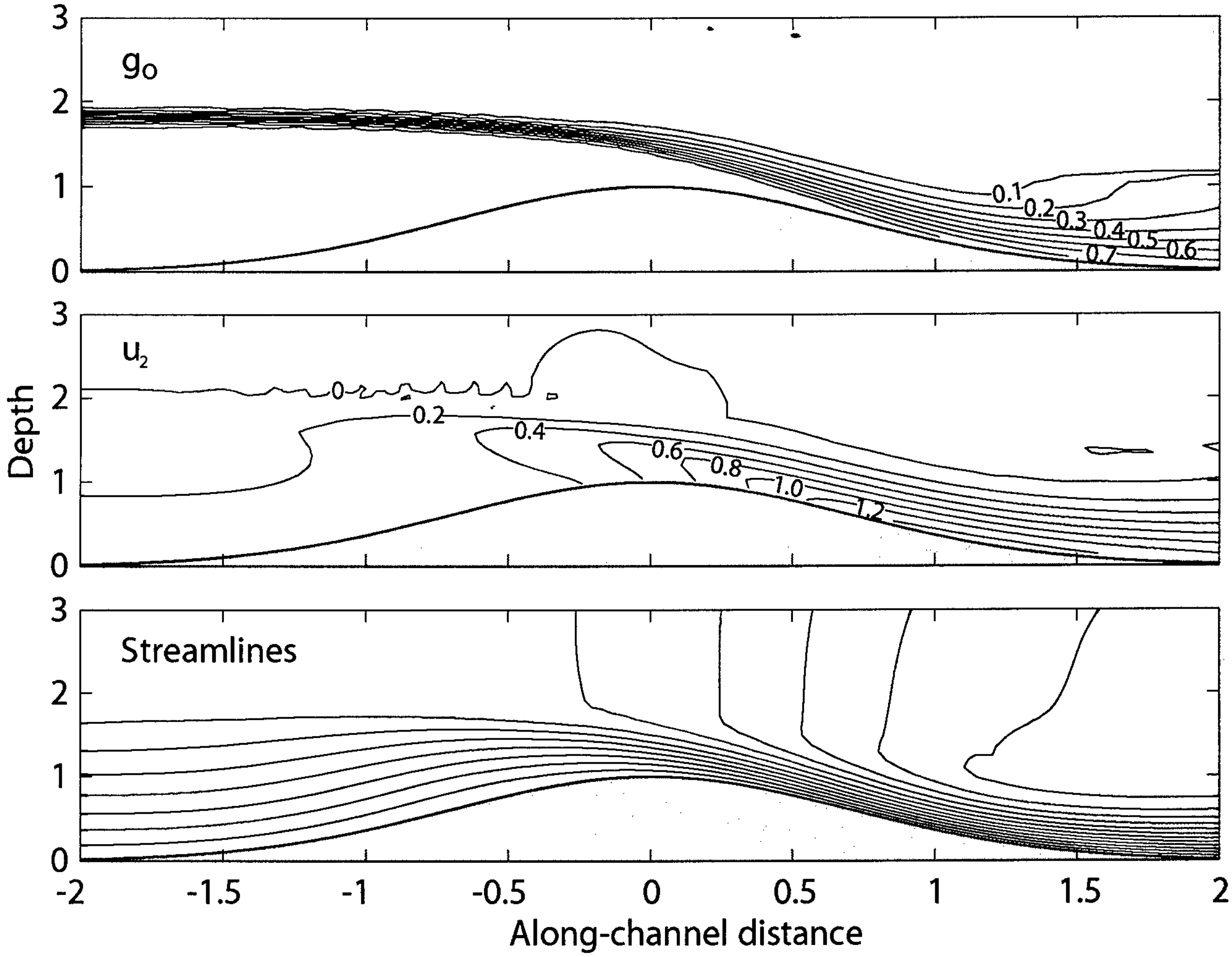

Figure 1. Continuously stratified exchange flow as computed by nonhydrostatic, two-dimensional model. The upper panel shows contours of density anomaly between the upper and lower layer; the middle panel shows contours of speed (left-to-right being positive); the lower panel shows the streamlines.

RESULTS

We have developed an extended version of the Taylor-Goldstein equation governing the normal modes of stratified shear flow in straits of arbitrary cross-sections. The eigenvalues of this equation are the phase speeds of the normal modes and their values determine whether the flow is hydraulically subcritical, supercritical or critical. The formulation of bounds on the phase speeds in terms of properties of the basic flow often allow the investigator to determine the hydraulic state without having to explicitly solve for the modes. This work is contained in Pratt, et al. (2000) and Deng et al. (2003). A demonstration of the use of the theorem appears in Figure 2. A numerical code for computing the normal modes has been created and is available to outside investigators.

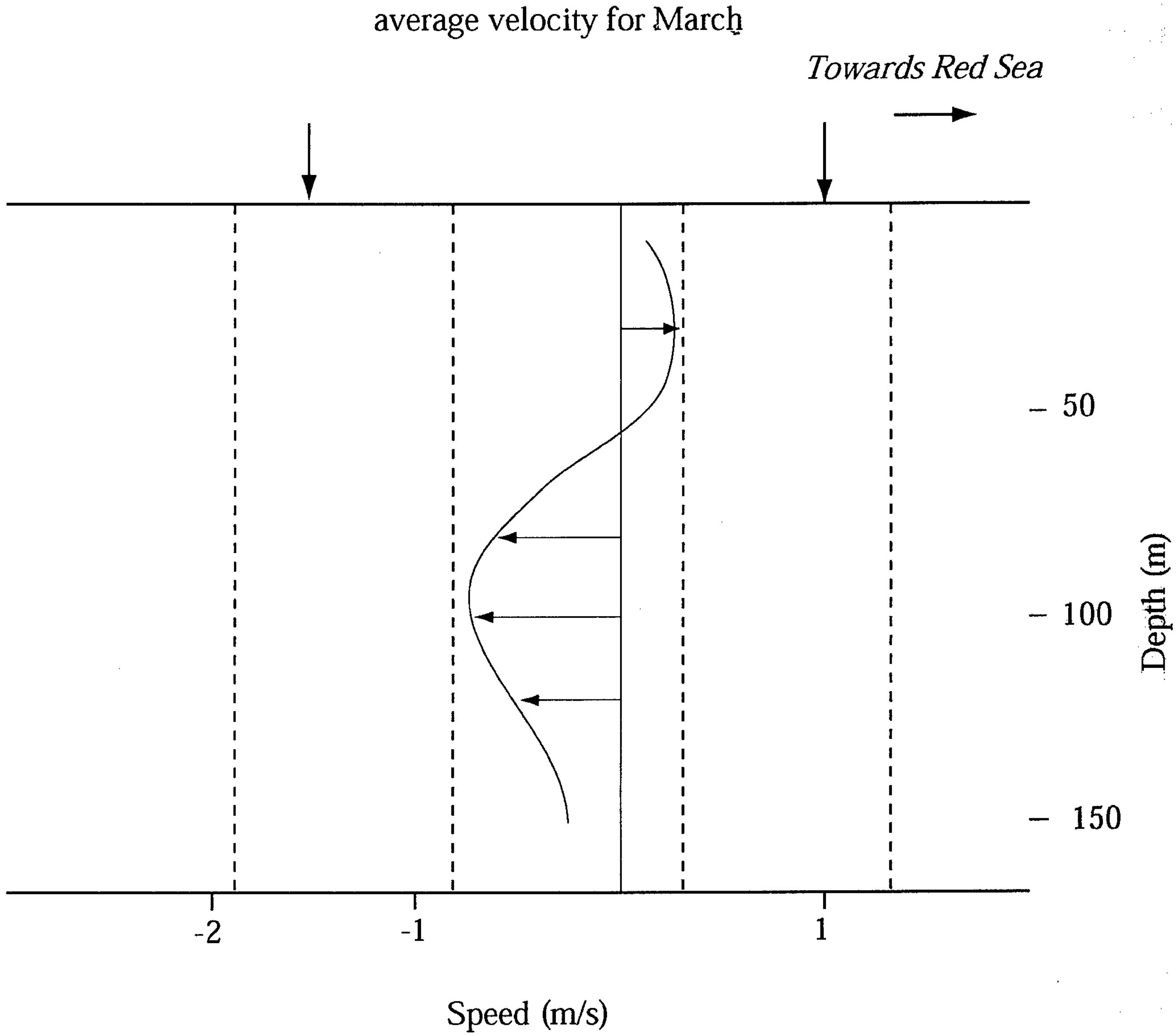

Figure 2: Illustration of the bounds formulated by Deng et al., 2003. The velocity profile belongs to a flow measured at the Bab al Mandab sill (see Murray and Johns, 1997 and Pratt et al., 2000). The two bands delineated by dashed lines show the possible ranges of horizontal propagation speed for each vertical normal mode pair. The bands indicate that each pair must have one positive value and one negative value;hence, this flow is subcritical.

Our study of critical layer mixing (Nielsen, et al. 2003) has resulted in an elevated understanding of the hydraulics of layers that have continuous stratification and shear and that are subject to entrainment from above. A generalized formulation of the shallow water equations for such a layer shows that the dynamics are always more inertial than would be the case if the density and velocity were vertically homogeneous. One consequence is that the critical section for a sill flow lies upstream from what would otherwise be expected. The enhanced inertia is measured by a new parameter that, if constant, allows the location of the critical section to be determined. Simulations from the nonhydrostatic model support these findings.

A study of the link between the outflow from a rotating strait and the circulation in an upstream basin has led to several remarkable results. We have found that while the distribution of forcing (including mass sources) in the basin has a dramatic effect on the basin circulation, the flow in the strait is relatively insensitive. In addition the strait flow found for various forcing distributions is that which tends to create maximum potential energy in the upstream basin. These results suggest the existence of certain universal strait flows that depend only on the rate of volume outflow and may lead to improved strategies for overflow monitoring. These findings are contained in Helfrich and Pratt (2003).

The numerical model used in the last study was also employed in a study of the paleoceanography of the Bosphorus and Black Sea (Sidall, et al., 2003). A simulation of the suspected ancient flood and infill 8400 years ago has produced jets and boundary currents in the entrance region of the Black Sea that are consistent to some extent with geological evidence of the flood. A significant result from the simulation is the formulation a downstream jet as the result of vorticity production in a hydraulic jump, a process that may be important in other outflows.

A workshop was held during April 15-19, 2002 in Villefranche-sur-Mer, France. Nearly all the leading authorities on the physical oceanography of sea straits attended the meeting. A special volume of Deep-Sea Research II with papers prepared by meeting participants is being edited by Pratt and David Smeed and is due to be published in 2004. Pratt has contributed a review paper (Pratt, 2004). A meeting report is attached to this document. A list of short papers prepared by review speakers and extended poster abstracts can be downloaded from the following sites:

http://www.soc.soton.ac.uk/JRD/PROC/STRAIT/talks.zip
http://www.soc.soton.ac.uk/JRD/PROC/STRAIT/posters.zip
http://www.soc.soton.ac.uk/JRD/PROC/STRAIT/report.zip

Pratt used a small percentage of support to make progress on a hydraulics textbook that he is writing with J. Whitehead. Publication in 2005 is expected.

IMPACT FOR SCIENCE

Our findings deepen the general understanding of the physics of hydraulics and mixing in sea straits, factors that play a prominent role in determining the stratification. The results will help guide investigators with the design of field experiments and monitoring strategies for specific straits as well as the formulation of numerical parameterizations.

RELATIONSHIPS TO OTHER PROGRAMS

One piece carried out by Pratt and Spall (2003) under funding from the ONR 'Predictability' DRI is related to the current project. It involves flow through complex topography consisting of numerous islands and straits and is relevant to archipelagos and ridge systems that act as partial barriers. Some of the work described above was carried out partially with NSF funding and has been acknowledged as such.

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